LLNL-JRNL-413929

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June 15, 2009

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ABSTRACT

An insulation system for ITER Central Solenoid must have sufficiently high electrical and structural strength. Design efforts to bring stresses in the turn and layer insulation within allowables failed. It turned out to be impossible to eliminate high local tensile stresses in the winding pack. When high local stresses can not be designed out, the qualification procedure requires verification of the acceptable structural and electrical strength by testing. We built two 4x4 arrays of the conductor jacket with two options of the CS insulation and subjected the arrays to 1.2 million compressive cycles at 60 MPa and at 76 K. Such conditions simulated stresses in the CS insulation. We performed voltage withstand tests and after end of cycling we measured the breakdown voltages between in the arrays. After that we dissectioned the arrays and studied micro cracks in the insulation. We report details of the specimens' preparation, test procedures and test results.

KEYWORDS: High voltage insulation, cyclic load, voltage breakdown, elastic module.

INTRODUCTION

ITER Central Solenoid (CS) will use an epoxy impregnated, glass-Kapton insulation system.

The CS will see high stress and high voltages during operation. Structural analyses have shown that the stresses in the insulation system may exceed allowables, especially as regards through-thickness tension and shear near the corners of the conduit. The main reason for high stresses is the large difference of the insulation coefficient of thermal expansion (CTE) (especially through thickness) with that of the conduit. Additional stress is imposed by bending of the conduit under high compressive load. To assure that the winding pack can maintain its structural and electrical integrity, we tested two insulation systems on a 4x4 array model of the winding pack under cyclic load in cryogenic conditions To quantify stresses in the model and in the real winding pack, we performed structural analyses to specify the load that would closely correspond to the conditions of the winding pack, a summary of which is given below. These analyses showed that the reasonably close stress environment will be reproduced at 60 MPa compression of the array. The number of load cycles of the CS during its proposed operating life is 60,000. With the ITER recommended safety factor (20), the number of cycles for testing was specified as 1.2 million. Testing was carried out at LN_2 temperature.

This test series closely follows a similar set performed during the CS Model Coil (MC) project in 1995 and 1996 [1]. This time there was no lateral support of the array because structural analysis showed that, to reach desired stress in insulation without this support, a lower force would be sufficient.

DESCRIPTION OF THE MATERIALS FOR TEST MODULES

Two test modules of 4 x 4 stacked, insulated conduits were prepared for this test series. The material of the jacket was JK2LB, a modified 316LN type alloy [6]. These modules contained two types of turn insulation (composed of E-glass and Kapton tape), identical layer insulation (E-glass cloth) placed horizontally between rows of conduit, and fill-in E-glass reinforcement placed at conduit corners and between columns of conduit. The entire ensemble of the stacked arrays was bonded together using vacuum-pressure impregnation with an epoxy resin.

The materials that were used for the electrical insulation of the test modules are .DGEBF epoxy (GY282) 100 parts by weight (PBW), MTHPA hardener (Aradur 918) 82 PBW, Accelerator (DY073-1), 0.25 PBW The resin ingredients were supplied by Huntsman, Inc. The resin system processing properties (working life/viscosity) were optimized for use in the CSMC.[2,3]

<u>Glass</u> <u>reinforcement</u>: For the layer insulation, an 8-harness satin-weave E-glass cloth (7781) with epoxy-compatible silane finish was used. Appropriate sizes of this cloth were cut from a commercial roll supplied by S.A. Robotics. This cloth has a nominal thickness of 0.29 mm.

For the turn insulation, an 8-harness satin-weave E-glass tape (1581) with epoxy-compatible silane finish was used. The tape was supplied in 50 mm (2 in) wide by 137m (150 yd) long by Carolina Narrow Fabrics. This tape is 0.23 mm (0.009 in) thick with side stitching, along both edges, about 0.32 mm thick.

<u>Electrical</u> <u>barrier</u>: Kapton type FPC film was used for the electrical barrier. This film was 0.05mm (0.002in) thick and supplied by American Durofilm in 51mm (2in) wide by 12m (40ft) long rolls. Type FPC is identical to type HPPST, a high-performance, surface

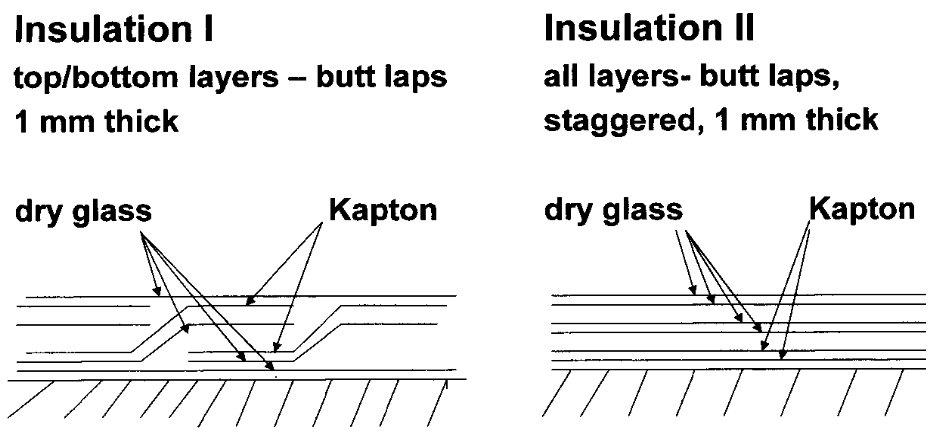

FIGURE 1. Two types of turn insulation used in test modules

treated polyimide film that has improved film adherence to epoxy resins. It was recommended by DuPont for use with epoxy resins.

End plugs: Each conduit end of both test modules contained a G10 plug. This provided adequate electrical insulation between the conduit contacts that were required for the voltage breakdown and withstand measurements. The end plugs were 49 x 49 mm and 25mm long with a cylindrical insert into the conduit of 32mm diameter and 12.5mm length.

INSULATION LAYUPS

Two specific electrical insulation systems were compared in this test series (FIGURE 1).

Turn insulation**:** Two different turn insulation system layups were tested in this series. These are illustrated in FIGURE 1. The first layup is: (1) one butt lap of 1581 E-glass tape; thickness ~ 0.32 mm, wound over conduit; (2) one ½ lap layer of cowound Kapton /1581 E-glass tape; thickness ~ 0.74 mm; (3) one butt lap of 1581 E-glass tape; thickness ~ 0.32

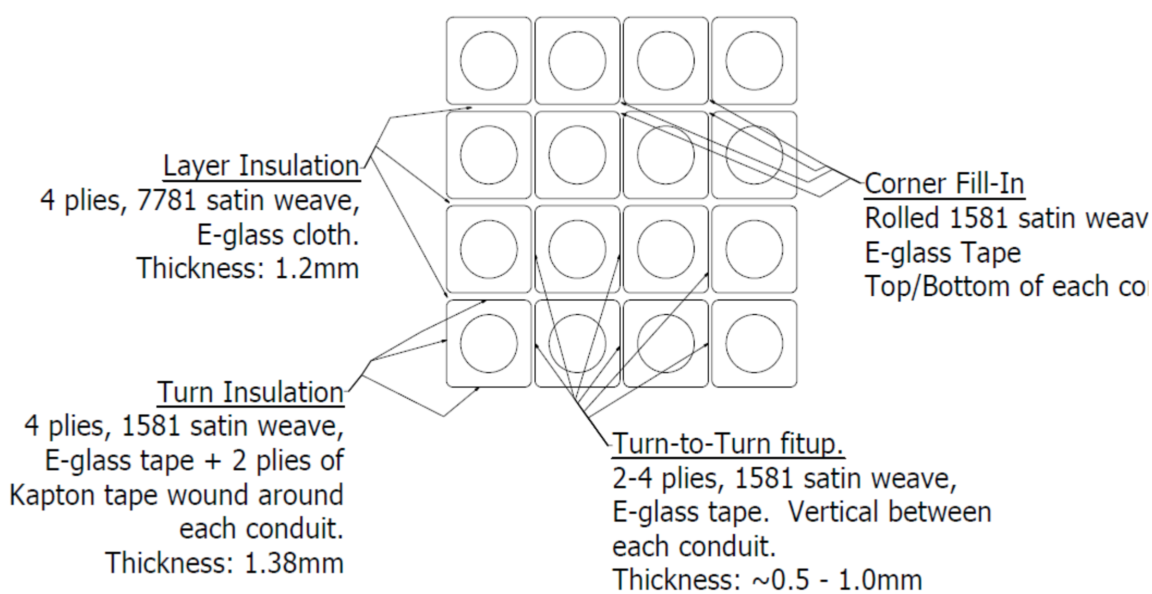

FIGURE 2. Schematic view and description of various insulation components in test modules

mm, top layer. Total thickness of the wrap insulation was 1.38 mm

The second layup is: one butt lap layer of Kapton tape; thickness ~ 0.05mm, wound over conduit one butt lap layer of Kapton tape; thickness ~ 0.05 mm, wound offset by 50% four butt lap layers of 1581 E-glass tape; thickness ~ 0.32 mm each, wound offset from previous layer by 50%; last layer is top layer. Total thickness of the wrap insulation was 1.38 mm. The layers of insulation were hand wound over both the conduit and end plugs. By initiation and termination of the winding over the end plugs, a continuous lapped winding was ensured over the conduit. After winding, the thickness of both turn insulation systems was measured and found to be about 1.38 mm; this was in excess of the design thickness of 1 mm. This increase was caused by the stitching along the edges of the glass tape; the stitching thickness was about 0.32 mm; the 1571 satin-weave tape thickness was 0.23 mm; each layer of Kapton was 0.05 mm. Layer insulation: The layer insulation, placed on the three horizontal planes between the four rows of conduit, consisted of 4 plies of E-glass cloth, 7781 satin weave.. This cloth had a nominal thickness of 0.29 mm; thus the total thickness was about 1.16 mm.

Test Modules Design

The insulation components for the two test modules include the following: (1) turn insulation – two styles, illustrated in Figure 1, wrapped around each conduit; (2) layer insulation – one style, four layers of 7781 E-glass cloth, positioned horizontally between each row of conduits; (3) turn-to-turn fill-in glass tape – 1581 E-glass tape segments to fill in gaps between turns in each layer, not to exceed 1mm thick, positioned vertically between each conduit; (4) corner fill-in – rolled E-glass tape and/or cut E-glass slits to fill in gaps between conduit corners, above and below each insulation layer.

The positions and materials of these components are illustrated and listed in Figure 2. The Test Module 1 had the insulation system II, with Kapton wrapped against bare metal. The Test Module 2 had the insulation system I.

STRESS ANALYSIS

The details of the stress analysis are reported in [4]. This study helped to determine the array configuration, number of conductors, their length, supports and boundary conditions, loads to simulate winding pack maximum stresses and expected deflections

TABLE 1. Properties of the array assumed for structural analysis.

		JK2LB	Insulation
E1 (along conductor axis)	Gpa	205	20
E2 (along wrap direction)	GPa	205	20
E3 (through thickness)	GPa	205	12
G12	GPa	78.8	6
G23	Gpa	78.8	6
G13	GPa	78.8	6
V12		0.3	0.17
V23		0.3	0.33
V13		0.3	0.33
Integrated CTE 1	%	0.21	0.22
Integrated CTE 2	%	0.21	0.22
Integrated CTE 3	%	0.21	0.643

TABLE 2. Summary of stress analysis of the 4x4 array

Load 60 MPa	Bounded				De-bounded				Kubo 2003	
Peak stresses, max (MX) and min (MN), MPa	Horizontal ins. web		Vertical ins. web	JK2LB	Horizontal ins. web		Vertical ins. web	JK2LB	Insulation (bonded)	JK2LB
Through thickness (Sx)										
SMX	5		55	88	16		42	145	54	
SMN	-143		-44	-71	-189		-24	-122	-165	
Wrap direction (Sy)										
SMX	38		15	9	63		14	18	15	
SMN	-45		-113	-332	-24		-73	-391	-101	
Along conductor axis(Sz)										
SMX		33		33		28		32		
SMN		-77		-32		-81		-40		
Shear stress										
SMXY		30				46			37	
SMXZ		6				7				
SMYZ		15				7				
S1(first principle stress)		58		92		73		148		401
SINT (Tresca)		121		322		231		383		592

from Kubo analysis [5]. There are two major concerns with the turn and layer insulation – high through-thickness stresses and high shear stresses and those we tried to match. It is not possible to match the CS winding pack stress distribution in the 4x4 array exactly but we tried to match as close as possible. TABLE 1 shows properties used for the array FEA.

Turn insulation with Option I is modeled as a fully bonded version. Option II is modeled as having a sliding surface with coefficient of friction of 0.3. Several models were built to study effect of variables on the stress conditions and it was determined that the length of the conduits in the array of 75 mm is sufficient, the load of 60 MPa without

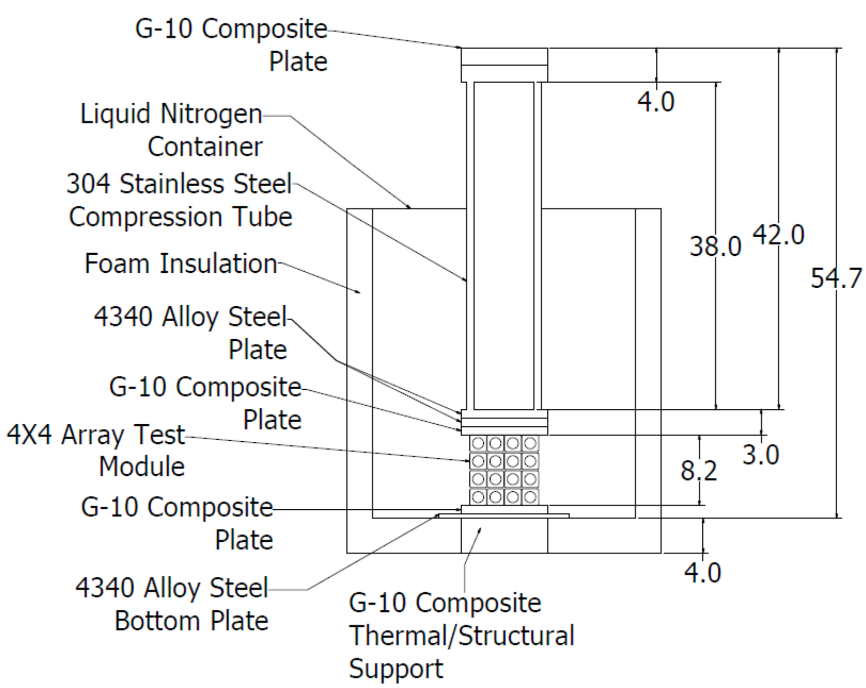

FIGURE 3. Compression-fatigue load train, cryostat, and test module assembly

lateral supports gives close stresses from the stress analysis prepared by Kubo for CS [5] in terms of through thickness stress and close in terms of peak shear stress. Stress analysis predicted significantly stiffer integrated elastic modulus for the bonded insulation system of Option I (55 GPa) than for the debonded system II (41 GPa) The summary of the stresses for the arrays is given in TABLE 2. Comparing bonded and debonded options, one can see debonded insulation has lower through thickness stress, but not near zero due to complex action of friction and pinching in the corners. The shear stress in the debonded system is a little higher, also counterintuitive result, again due to pinching and friction. The other difference between these two systems is noticeably higher stresses in the conduit in the debonded system due to less interaction and load distribution among the neighbors.

Cryogenic Testing of the Arrays Setup

The schematic of the experiment is shown in FIGURE 3. Compression-fatigue tests at 76 K were conducted at the National Institute of Standards and Technology, Materials Reliability Division, Boulder, Colorado. A maximum stress of 60MPa on the coil pack was achieved with a load of 1.26 MN. The fatigue tests were conducted to 1.2 million cycles with R ratios of 0.1-0.2. The test modules were periodically warmed to room temperature to conduct voltage-withstand tests between conduits. After completion of 1.2 million cycles, voltage-breakdown tests were conducted at room temperature.

TEST RESULTS

For this project, we measured the elastic modulus of each test module and conducted voltage withstand tests between individual insulated conduits of each test module during the process of compression-fatigue testing to 1.2 million cycles at 76 K.

Electrical Measurements

Voltage withstand and breakdown tests between insulated conduits for both layer and turn insulation were conducted using a Hipotronics Model HD140 HiPot tester with a maximum voltage of 40 kV. All measurements were conducted in air at room temperature in the dc mode. Voltage ramp rates of 1kV per 10–15 s were employed. The procedure for voltage withstand tests is to ramp the voltage to a given voltage (in our case, 2.2 kV), hold for one minute, and to ramp down to zero voltage.

The maximum voltage between two layers is determined as 600 V [7] and the test voltage was determined as two times operating voltage plus 1 kV, which gave 2.2 kV. The objective of this test is to assess the insulation capability of a given system to withstand that prescribed voltage.

The electrical contacts were placed, alternately, on opposite sides of the test module to permit both turn and layer insulation testing of adjacent conduits. For these tests, voltage breakdown is defined as the voltage at which an electrical path through the insulation is created that leaves a carbonized path, such that subsequent applications of applied voltage will result in much lower insulation capability by following the same breakdown path through the insulation system. *Tracking* is defined as a voltage breakdown through the dielectric media (in our case, air at room temperature) from one electrical contact to the other contact, bypassing a path through the insulation system. After tracking, a repeated voltage ramp-up will result in breakdown at the equivalent voltage, or even higher voltage, since no carbonized path through the insulation system was created during the breakdown.

Tracking was observed in the testing of some of the 4 x 4 array conduit pairs. In these cases we found that condensed air, in the form of water droplets, contributed to the electrical conductivity of the air at room temperature and, thus, assisted in the promotion of electrical tracks that bypassed the insulation system. These water droplets were created along, and on, the G10 end plugs during the warmup from liquid nitrogen; they had not been properly evaporated during the warmup cycle of, in some cases, more than one day under hot air blowing, dry-out procedures.

Preliminary measurements on dry glass/Kapton and exclusively dry glass layups, some identical to those used to produce the coil packs, were conducted. As expected, the presence of Kapton adds considerably to the breakdown resistance, much higher than specified 2.2 kV. The voltage breakdown for only one glass layer (separated by only 0.23mm) is about equivalent to the withstand voltage (2.2 kV) that was used during the fatigue tests.

All 2.2 kV tests passed. Tests on 8 pairs on Test Module I produced tracking breakdown results from 22–40 kV for 1st and 2nd tests owing to high moisture content, but after drying, all tests passed 40 kV with no breakdown.

Test Module II, in the first test for 3 pairs voltage breakdowns of 37, 37, and 39 kV were recorded. The second, repeated test of these pairs resulted in no breakdowns at 40 kV.

Elastic Modulus of the Arrays

Elastic moduli of the arrays were measured in the range of 20-60 MPa after calibrating against Al block with known properties. The results are given in FIGURE 4. The moduli are close to each other and close to the bonded model for the insulation system This suggests that the Test Module 1 did not have really sliding interface everywhere due to resin penetration underneath the Kapton and therefore was more constrained than assumed in analysis. In visual inspection of the Test Module 1 (with insulating system II) one could see dry and wet areas under the Kapton.

OPTICAL INSPECTION OF INSULATION

Visual Comparison after VPI Processing Before Fatigue Testing

There was very limited porosity that was observable within both test modules. Several areas on each test module had lack of resin penetration. The two test modules showed similar characteristics. This lack of resin penetration usually occurred along the exterior sides of the test modules, not the front and back sides that had the end plugs exposed. Some side lengths for incomplete resin flow were up to 5–7 cm in length; there were two of these in each test modules. Several much smaller areas were also present in each module.

Visual Comparison after Testing Prior to Cross-Sectioning

Both test modules exhibited similar appearances following exposure to 60 MPa compressive stress and to 1.2million fatigue cycles at 76 K. The surface of each test module contained cracking of the resin along the interfaces between conduit interfaces. These surface cracks did not appear to increase in distribution or size with increased fatigue cycles, but, instead, formed predominantly during the initial cool down and early fatigue cycles. We could detect no distinct difference in the appearance or distribution of these cracks along the conduit interfaces for the two test modules.

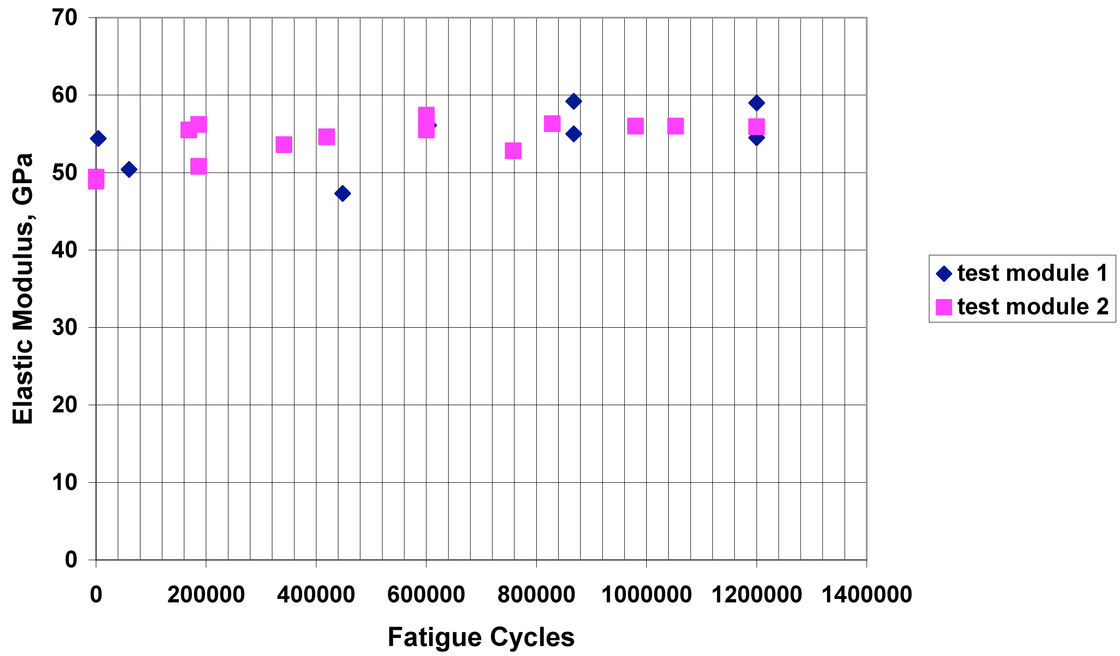

FIGURE 4. The elastic moduli of both test modules as a function of number of fatigue cycles at 76 K with a maximum compressive stress of 60 MPa.

At the front and back sides of the test modules, the G10 end plugs were exposed with a thin layer of cured neat resin (~ 1mm) over their surfaces. The resin surfaces of the end plugs of each module all showed evidence of crazing (thin microcracks). This was in contrast to the appearance of much larger cracks on the surface of the CSMC test modules that were tested to a much higher (90–100 MPa) compressive stress (but much lower number of fatigue cycles) at 77 K. On the glass-reinforced resin surfaces on each side of the test modules there was no evidence for crazing or cracking of the resin.

Visual and Optical Microscopic Observations

To obtain detailed observations after testing, the 4x4 array test modules were cut in two parts, one part having 25 mm of conduit length, the other having 75 mm of conduit length. The 25 mm conduit length (plus 25 mm of end plug) part was then carefully ground and polished to produce a surface finish sufficient for optical microscopy observations. The color pictures of the cracks could be found in [8], they are difficult to reproduce in the B&W proceedings, therefore we limit ourselves to a brief description and summary of our observations.

Test Module 1 (TM1): Throughout both test modules there were sections (areas between parallel conduit walls) that had no cracking, but most corners contained cracks, consistent with analysis.

In TM1 an attempt was made to add glass to the corner areas by extending the vertical sections of added glass plies into the corner area. Sometimes that was not successful in preventing cracks formation.

We observed that the layer insulation serves to limit and arrest cracking in the corner areas. Additionally, very few cracks were detected within the layer insulation. Some cracks extended from the corner areas horizontally between the layer and turn insulation. No cracking was associated with the Kapton in TM1. There were areas where the Kapton has slightly detached from the conduit walls, yet there were no adverse consequences of this. In all cases, there was no evidence of resin penetration around the Kapton tape laps to reach the conduit walls.

Test Module 2 (TM2): Extensive cracking was observed at most conduit corners. The layer insulation served to separate the top and bottom areas of cracking at the conduit corner intersections and remained relatively crack free. The layer insulation appears to provide needed structural stability at the conduit corners. Sometimes cracking was observed within the turn insulation around a conduit corner.

Turn insulation cracking is also sometimes observed along a vertical section; the frequency of this type of cracking was less than at corners or within horizontal sections of the turn insulation of the conduits. Kapton is shown to limit the area of cracking and, thus, acts as a crack arrestor.

Within the vertical sections of parallel conduit walls, less cracking was observed. Cracking not only occurred within the turn insulation, but, also, sometimes between the turn and layer insulation in the horizontal sections.

Wherever extensive cracking occurs, it is completely bounded by the Kapton laps and restricted to the area between the conduit wall and first Kapton layer. It is likely that these examples of extensive cracking originated from lack of complete resin penetration through the ½ laps of cowound glass/Kapton during the resin transfer process

Some pictures show that both horizontal and vertical sections may have cracking either within the turn insulation or within the insulation between the turn insulation but not within the layer insulation.

DISCUSSION

Neither the property measurements nor observations of test module surface effects were effective in distinguishing significant relative performances of the two insulation systems. From observations of the cross-sectioned 4 x 4 arrays we noticed some differences in the cracking behavior of the two test modules based on the position of the Kapton within the insulation system. In Test Module 1, the Kapton tape was wound over the conduit walls, followed by 4 layers of glass tape; this appeared to effectively increase the area for undisrupted resin flow along both the vertical and horizontal sections. In Test Module 2 the Kapton was cowound (1/2 lap configuration) with glass tape and, thus, was enclosed within the glass reinforcement. In the Test Module 2 configuration, the Kapton impeded the resin flow (resulting in lack of penetration), but also acted to both arrest and contain adjacent cracks.

During fabrication of the 4 x 4 arrays we noticed the following differences between the butt lap taping approach used for test module 1, as contrasted with the ½ lap, cowound taping process for the Kapton/glass component of the insulation system that was used in test module 2:

(1) Taping of ½ lap components is much easier than of butt lap components. The dimensional tolerance for adjacent laps is less for the ½ configuration, whereas the butt lap configuration demands relatively precise dimensional control to preclude gaps between the adjacent turns or overlap of the adjacent turns.

(2) The ½ lap configuration is less sensitive to external handling of the insulated conduit for two reasons: (a) bending of the conduit tends to create a gap between the butt-lap turns, whereas the ½ lap turns have additional frictional stress between consecutive turns that removes this concern. (b) The use of external handling devices or grips tends to promote sliding apart of the butt-lapped turns, whereas the ½ lap adjacent turns again have additional frictional stresses between the adjacent turns that resist this sliding feature.

CONCLUSIONS

We qualified two options of the CS insulation by testing in relevant cryogenic and mechanical-load conditions. Both options met the criteria with large margins. We demonstrated that even with limited cracking the insulation system ensures sufficient electrical strength and structural integrity for 20 times the specified life of the CS.

ACKNOWLEDGEMENTS

J. Schultz skillfully conducted all of the electrical measurements. Optical and scanning microscopy photographs of the cross-sectional 4 x 4 arrays were provided by C. McCowan of NIST; we are deeply indebted to Chris for his exceptional pictures of the insulation sections of the test modules. The authors wish to thank R. Rentz of NIST for his diligent and careful work in assisting our compression-fatigue test program. Other NIST staff who provided much needed assistance were T. Siewert, R. Santoyo, and E. Drexler.

J. Shepic, well-known for his contributions to strain-gage extensometer improvements and careful work, provided his usual outstanding work in preparation of our four extensometer post design for these experiments. J. Steven of J&D Machine Technology skillfully and timely contributed to the machining of all load train components.

We thank S.J. Kenney for help in preparation of the manuscript.

This work performed under the auspices of the U.S. Department of Energy by Oak Ridge National Laboratory under contract DE-AC05-00OR22725 and by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

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